

**SYNERGY OF COMBINED LHC AND LC ANALYSES IN SUSY SEARCHES**G. MOORTGAT-PICK<sup>a</sup>*Institute for Particle Physics Phenomenology, University of Durham, South Road,  
Durham DH1 3LE, England*

We present a case study for the synergy of combined LHC and LC analyses in Susy searches where simultaneous running of both machines is very important. In case that only light non-coloured Susy particles are accessible at a Linear Collider with an initial energy of  $\sqrt{s} = 500$  GeV, the precise analysis at the LC nevertheless leads to an accurate Susy parameter determination. This allows the prediction of heavy Susy particles. Providing these LC results as input for LHC analyses could be crucial for the identification of signals resulting in a direct measurement of the heavy neutralinos. These results provide an important consistency test of the underlying model. Furthermore, feeding back the LHC results into LC analyses leads to an improvement in the parameter determination.

**1 Introduction**

One of the best motivated extensions of the Standard Model (SM) is Supersymmetry (Susy). Therefore Susy searches will get a large weight at the new physics searches at the Large Hadron Collider (LHC), whose first run is foreseen for 2007 and where data taking is expected to continue for about 20 years. Since Susy, if realised in nature, has to be a broken symmetry, a large amount of new parameters enter in addition to the 19 SM free parameters. They have to be precisely determined in order to reveal the underlying structure of the model. In the Minimal Supersymmetric Standard Model (MSSM) one is faced with around 105 new free parameters. Therefore care is required to impose as little model assumptions on the experimental analyses as possible. Due to the clear signatures at the Linear Collider (LC) a largely model-independent determination of masses, couplings, mixing angles, phases and quantum numbers can be done in the general MSSM parameter space. Therefore significant help for LHC analyses via particle mass measurements and predictions from analyses at a LC is expected. Searches for light new particles at a LC with a first energy phase of  $\sqrt{s} = 500$  GeV, which could start running at 2015,

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<sup>a</sup>email address: g.a.moortgat-pick@durham.ac.uk

may be crucial. The mass predictions from the LC may lead to a precise mass measurement of heavy new particles via the LHC analyses. Therefore, the interplay of both colliders will provide a powerful consistency check of the model at an early stage of both experiments and may outline future strategies for new physics searches at the LHC. Furthermore, feeding back the LHC results increases the accuracy of the fairly model-independent Susy parameter determination at the LC<sup>1</sup>.

Interest in working out such examples of a synergy between both experiments was initiated by the world-wide LHC/LC study group<sup>b</sup>, founded in 2002. The results so far are summarised in a working group report<sup>2</sup>.

We choose as a representative example the Susy reference scenario SPS1a<sup>3</sup> which is a quite favourable parameter point for both machines where already some experimental simulations exist. While SPS1a is based on an mSugra scenario, i.e. the Susy breaking is transmitted via gravitational interactions, for the further procedure we do not make any assumptions depending on the Susy breaking scenario. In the following we mainly concentrate on the non-coloured particle sector.

## 2 Susy studies at the LHC

Detailed simulations of the LHC capabilities for the reference point SPS1a were carried out<sup>4</sup>; the masses of the Susy particles can in most cases only be studied by analysing complicated decay chains, like

$$\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q \rightarrow \tilde{\ell}_R^\mp \ell^\pm q \rightarrow \tilde{\chi}_1^0 \ell^\mp \ell^\pm q, \quad (1)$$

which might be difficult to resolve. The precise reconstruction of the states in the decay chains requires in particular the knowledge of the mass of the lightest Susy particle (LSP), which is often assumed to be stable. As an example for the strong sensitivity to  $m_{\tilde{\chi}_1^0}$  we show in Fig. 1 (left) the determination of  $m_{\tilde{\ell}_R}$  in dependence of  $m_{\tilde{\chi}_1^0}$ <sup>4</sup>. Applying a joint fit of various kinematic 'edges' yields an overconstraint system and leads to an indirect knowledge on  $m_{\tilde{\chi}_1^0}$ . However, some assumptions about particle identities have to be made. Using LC results leads to a higher accuracy in determining the masses and provides model-independent consistency tests.

In our reference point simulations were done to determine also the gaugino/higgsino particles. The second lightest neutralino can be identified in the opposite sign-same flavour signal (OS-SF) with an uncertainty of about  $\delta m_{\tilde{\chi}_2^0} = 4.7$  GeV. The main background from  $\tilde{\chi}_1^\pm$  decays yields an equal number of (OS-SF) and Opposite-Sign Opposite-Flavour (OS-OF) leptons pairs and can thus be separated by subtraction<sup>5</sup>.

The heavy charged and the neutral gaugino/higgsino particles are nearly mass degenerate. The resolution of the corresponding edges is therefore particularly difficult. The neutralino  $\tilde{\chi}_3^0$  is nearly a pure higgsino and does not couple to squarks, therefore only  $\tilde{\chi}_2^\pm$  and  $\tilde{\chi}_4^0$  are accessible. The competing decay chains in this case are

$$\tilde{\chi}_4^0 q \rightarrow \tilde{\ell}_R^\pm \ell^\mp q \rightarrow \tilde{\chi}_1^0 \ell^\pm \ell^\mp q \quad (2)$$

$$\tilde{\chi}_4^0 q \rightarrow \tilde{\ell}_L^\pm \ell^\mp q \rightarrow \tilde{\chi}_1^0 \ell^\pm \ell^\mp q \quad \text{or} \quad \tilde{\chi}_2^0 \ell^\pm \ell^\mp q \quad (3)$$

$$\tilde{\chi}_2^\pm q' \rightarrow \tilde{\nu}_\ell \ell^\pm q' \rightarrow \tilde{\chi}_1^\pm \ell^\mp \ell^\pm q' \quad (4)$$

In combination with measured invariant masses one can derive the OS-SF signal of the heavy particle with  $\delta(m) = 5.1$  GeV, and under specific assumptions one can interpret the edge as that of the  $\tilde{\chi}_4^0$  particle<sup>4,5</sup>.

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<sup>b</sup>webpage: <http://www.durham.ac.uk/~georg/lhclc>

### 3 Susy studies at the LC

Precise simulations for the mass measurements of the sleptons and the light charginos and neutralinos at the Linear Collider have also been done for the parameter point SPS1a<sup>6,7</sup>, the results are given Table 1. Particularly interesting is the high accuracy in the determination of  $m_{\tilde{\chi}_1^0}$  with  $\delta(m_{\tilde{\chi}_1^0}) = 0.05$  GeV from  $\tilde{e}_R$  decays, but also the accuracy  $\delta(m_{\tilde{\chi}_1^\pm}) = 0.55$  GeV and  $\delta(m_{\tilde{\chi}_2^0}) = 1.2$  GeV are important. Due to  $\tan\beta = 10$  in the chosen parameter point the light chargino  $\tilde{\chi}_1^\pm$  as well as the second lightest neutralino  $\tilde{\chi}_2^0$  decay both mainly into  $\tilde{\tau}$ 's producing a signal similar to that of stau-pair production. The final states from  $\tilde{\chi}_1^+ \tilde{\chi}_1^-$  and  $\tilde{\chi}_1^0 \tilde{\chi}_2^0$  decays are the same (2  $\tau$ + missing energy), however with different topology. This feature allows to separate the process to some extent exploiting e.g. suitable cuts on the opening angle between the leptons.

The precise measurement of the Susy particle masses as well as the different cross sections of this light particle spectrum alone leads to a precise determination of the fundamental Susy parameters which govern the chargino-neutralino sector. Within the general MSSM, from these parameters the masses of the heavier neutralinos and the heavier chargino can be predicted without further model assumptions.

#### 3.1 Strategy for Susy parameter determination

We follow, as an example, a method described in<sup>8</sup> and take into account in addition the simulated errors in the mass and cross section measurements<sup>1</sup>. The mass matrix  $\mathcal{M}_C$  of the charged gauginos  $\tilde{W}^\pm$  and higgsinos  $\tilde{H}^\pm$  depends on  $M_2$ ,  $\mu$ ,  $\tan\beta$ . The mass eigenstates are the two charginos  $\tilde{\chi}_{1,2}^\pm$ . For real  $\mathcal{M}_C$  the two unitary diagonalisation matrices can be parameterised with two mixing angles  $\Phi_{L,R}$ . The mass eigenvalues  $m_{\tilde{\chi}_{1,2}^\pm}^2$  and the mixing angles are given by the Susy parameters, see e.g.<sup>9</sup>. The cross section  $\sigma^\pm\{ij\} = \sigma(e^+e^- \rightarrow \tilde{\chi}_i^\pm \tilde{\chi}_j^\mp)$  can be expressed as a function of  $(\cos 2\Phi_{L,R}, m_{\tilde{\chi}_i^\pm}^2)$ ; the coefficients for  $\sigma^\pm\{11\}$  are explicitly given in Ref.<sup>1</sup>. The chargino cross sections are measured at  $\sqrt{s} = 400$  GeV and 500 GeV with polarised beams so that the mixing angles  $\cos 2\Phi_{L,R}$  can unambiguously be determined. Together with  $m_{\tilde{\chi}_1^\pm}$  the parameters  $M_2$ ,  $\mu$ ,  $\tan\beta$  can be derived.

The neutralino mixing matrix  $\mathcal{M}_N$  depends on  $M_1$ ,  $M_2$ ,  $\mu$  and  $\tan\beta$ . Analytic expressions for the mass eigenvalues  $m_{\tilde{\chi}_{1,\dots,4}^0}^2$  and the eigenvectors are e.g. given in<sup>8</sup>. The characteristic equation of the mass matrix squared,  $\mathcal{M}_N \mathcal{M}_N^\dagger$ , can be written explicitly<sup>1</sup> as a quadratic equation of the U(1) gaugino mass parameter  $M_1$ . Together with the kinematically accessible cross sections for the light neutralino production,  $\sigma_{L,R}^0\{12\}$  and  $\sigma_{L,R}^0\{22\}$ , a precise and unambiguous determination of  $M_1$ ,  $M_2$ ,  $\mu$  and  $\tan\beta$  can be performed without assuming a specific Susy breaking scheme.

#### 3.2 Results

We took into account the following uncertainties:

- The uncertainties in the mass measurement, see Table 1.
- With  $\int \mathcal{L} = 500 \text{ fb}^{-1}$  at the LC, we assume  $100 \text{ fb}^{-1}$  per each polarisation configuration and we take into account  $1\sigma$  statistical errors for the cross sections.
- The beam polarisation measurement is assumed with an uncertainty of  $\Delta P(e^\pm)/P(e^\pm) = 0.5\%$ .
- Since the chargino (neutralino) production is sensitive to  $m_{\tilde{\nu}_e}$  ( $m_{\tilde{e}_{L,R}}$ ), we include the experimental errors of their mass determination of 0.7 GeV (0.2 GeV, 0.05 GeV), see Table 1.
- Concerning the neutralino cross sections we estimate the statistical error based on an experimental simulation<sup>7</sup> yielding an efficiency of 25% and include an additional systematic error ( $\delta\sigma_{\text{bg}}$ ) which takes into account the uncertainty in the background subtraction, for details

see<sup>1</sup>.

The dominant error in the cross sections is the statistical error and reaches up to  $\sim 4\%$  for left-handed polarised beams and up to  $\sim 16\%$  for right-handed polarised beams due to partially low rates, see Table 3. The other dominant error is due to the uncertainty in the mass measurement of  $\delta(m_{\tilde{\chi}_1^\pm})$  which results in an error of about 2-3% in the cross sections. The errors caused by the uncertainty in the beam polarisation  $\Delta P(e^\pm)/P(e^\pm) = 0.5\%$  lead to errors  $\ll 1\%$  for left-handed beams and up to  $\leq 2\%$  for right-handed beams. Errors caused by the mass uncertainties of the exchanged particles are  $\ll 1\%$ .

Such a precise analysis of the light particle spectrum leads to a very accurate determination of the underlying fundamental Susy parameters. We use a 3-parameter  $\Delta\chi^2 = \sum_i |(O_i - \bar{O}_i)/\delta O_i|^2$  test, yielding

$$M_1 = 99.1 \pm 0.2, \quad M_2 = 192.7 \pm 0.6, \quad \mu = 352.8 \pm 8.9, \quad \tan \beta = 10.3 \pm 1.5. \quad (5)$$

Since the light particles in our reference scenario are mainly gaugino-like we derive precise values for the gaugino mass parameters  $M_{1,2}$ , but less accurate values for the higgsino mass parameter  $\mu$  and for  $\tan \beta$ . However, the determination of the parameters is sufficient to predict the heavier chargino and neutralino masses with high precision:

$$m_{\tilde{\chi}_2^\pm} = 378.8 \pm 7.8, \quad m_{\tilde{\chi}_3^0} = 359.2 \pm 8.6, \quad m_{\tilde{\chi}_4^0} = 378.2 \pm 8.1. \quad (6)$$

#### 4 Susy studies in combined LHC/LC analyses

Feeding some results of the LC analysis, i.e. the mass predictions as well as the precisely measured masses of the light Susy particles,  $m_{\tilde{\chi}_1^0}$ ,  $m_{\tilde{\chi}_1^\pm}$ ,  $m_{\tilde{e}_{L,R}}$ ,  $m_{\tilde{\nu}}$ , as input into the LHC analysis leads to the following improvements at the LHC analysis:

- increase of statistical sensitivity due to the mass predictions ('look elsewhere effect'), which could be crucial for the search for statistically marginal signals;
- clear identification of the dilepton edge from the  $\tilde{\chi}_4^0$  decay chain;
- accurate measurement of  $m_{\tilde{\chi}_4^0} = 377.87 \pm 2.23$  GeV;
- the precise identification of a dilepton edge right at the predicted mass with the help of the LC means an important check of the underlying Susy model at an early stage of both experiments, the LHC in combination with a LC<sub>500</sub>;
- better accuracy also for  $\delta(m_{\tilde{\chi}_2^0}) = 0.08$  GeV due the precise knowledge on the LSP mass,  $m_{\tilde{\chi}_1^0}$ .

Using these improved results from the LHC analysis as input for further analyses at the LC leads also to an improvement in the Susy parameter determination. Since for our reference point the heavier neutralino states are mainly higgsino-like, we increase thus in particular the accuracy on the higgsino mass parameter,  $\mu = 352.4 \pm 2.1$  GeV, and on  $\tan \beta = 10.2 \pm 0.6$ , see also Table 2.

#### 5 Conclusions

Future experiments will face the task to unravel possible kinds of physics beyond the SM. We have shown a representative case study where searches for new physics models – we have chosen Supersymmetry – may greatly benefit from the synergy of the combined analysis at the LHC and at the LC in its first energy stage of  $\sqrt{s} = 500$  GeV.

We studied the prospects for resolving the Susy gaugino/higgsino sector. We focused on the situation where only the light states ( $\tilde{\chi}_1^0$ ,  $\tilde{\chi}_2^0$ ,  $\tilde{\chi}_1^\pm$ ) are accessible at the first stage of the LC. For a representative example of the MSSM, we perform a precise determination of the fundamental SUSY parameters at the LC. The masses of heavier chargino and neutralinos can be subsequently predicted at the level of a few percent.

Table 1: Chargino, neutralino and slepton masses in SPS1a, and the simulated experimental errors at the LC<sup>6,7</sup>. It is assumed that the heavy chargino and neutralinos are not observed at the first phase of the LC operating at  $\sqrt{s} \leq 500$  GeV. [All quantities are in GeV.]

	$\tilde{\chi}_1^\pm$	$\tilde{\chi}_2^\pm$	$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_4^0$	$\tilde{e}_R$	$\tilde{e}_L$	$\tilde{\nu}_e$
mass	176.03	378.50	96.17	176.59	358.81	377.87	143.0	202.1	186.0
error	0.55		0.05	1.2			0.05	0.2	0.7

Table 2: Susy parameters with  $1\sigma$  errors derived from the LC data collected at the first phase of operation and of the combined analysis of the LHC and LC<sub>500</sub> data with  $\delta(m_{\tilde{\chi}_2^0}) = 0.08$  GeV and  $\delta(m_{\tilde{\chi}_4^0}) = 2.23$  GeV derived from the LHC when using the LC input of  $\delta(m_{\tilde{\chi}_1^0}) = 0.05$  GeV<sup>1</sup>.

	$M_1$	$M_2$	$\mu$	$\tan\beta$
theo	99.1	192.7	352.4	10
LC <sub>500</sub>	$99.1 \pm 0.2$	$192.7 \pm 0.6$	$352.8 \pm 8.9$	$10.3 \pm 1.5$
LHC+LC <sub>500</sub>	$99.1 \pm 0.1$	$192.7 \pm 0.3$	$352.4 \pm 2.1$	$10.2 \pm 0.6$

Concerning studies at the LHC the mass predictions from the LC analysis lead to an increase of statistical sensitivity. Together with a precise knowledge on the LSP mass and the light slepton masses measured at the LC, the mass predictions lead to a clear identification of the heavy neutralinos in the corresponding decay chains at the LHC analysis, followed by precise mass measurements of these heavy particles.

Measuring the heavy particles right at the predicted masses provides an important check of the underlying Susy model. Furthermore, feeding back the LHC results, i.e. the now clearly identified and measured heavy electroweak particles, into further analysis at the LC<sub>500</sub> leads to an even more accurate determination of the Susy parameters  $M_1$ ,  $M_2$ ,  $\mu$  with an accuracy at the  $\leq O(1\%)$  level, and an error on  $\tan\beta$  of the order of  $\leq 10\%$ . At this stage of accuracy radiative corrections become relevant in the electroweak sector<sup>10</sup>, which will have to be taken into account in future fits<sup>11</sup>.

The analysis has been performed within the general frame of the unconstrained MSSM. Our strategy does not rely on any particular relations among the fundamental parameters, like the GUT or mSUGRA relations, and therefore is applicable for arbitrary MSSM parameters which lead to a phenomenology similar to the one studied.

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Table 3: Cross sections of the processes  $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$ ,  $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0$ ,  $e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$  at  $\sqrt{s} = 400$  GeV and  $\sqrt{s} = 500$  GeV, respectively, with  $P_{e^-} = -80\%$ ,  $P_{e^+} = +60\%$  ( $\sigma_L$ ) and  $P_{e^-} = +80\%$ ,  $P_{e^+} = -60\%$  ( $\sigma_R$ )<sup>1</sup>.

	$\sqrt{s} = 400$ GeV		$\sqrt{s} = 500$ GeV	
$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$	$\sigma_L = 215$ fb	$\sigma_R = 6$ fb	$\sigma_L = 504$ fb	$\sigma_R = 15$ fb
$\tilde{\chi}_1^0 \tilde{\chi}_2^0$	$\sigma_L = 148$ fb	$\sigma_R = 20$ fb	$\sigma_L = 168$ fb	$\sigma_R = 21$ fb
$\tilde{\chi}_2^0 \tilde{\chi}_2^0$	$\sigma_L = 86$ fb	$\sigma_R = 2$ fb	$\sigma_L = 217$ fb	$\sigma_R = 6$ fb

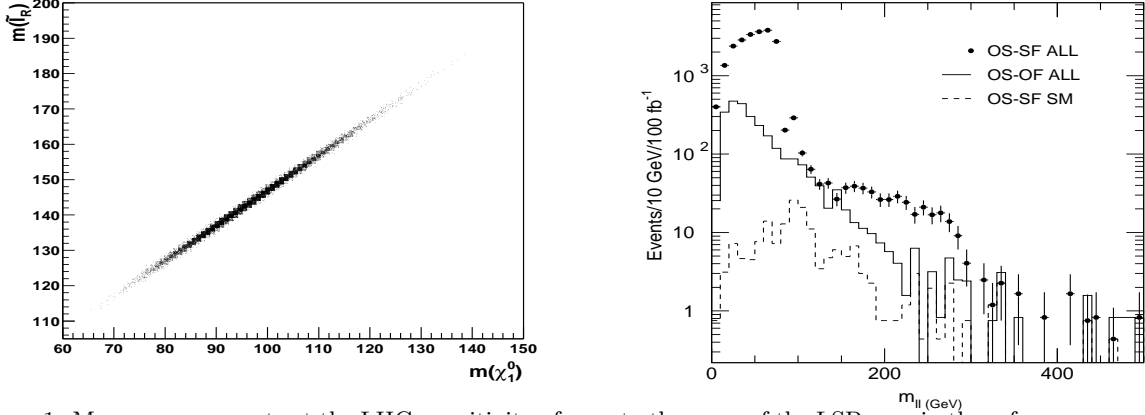


Figure 1: Mass measurements at the LHC: sensitivity of  $m_{\tilde{\ell}_R}$  to the mass of the LSP  $m_{\tilde{\chi}_1^0}$  in the reference scenario SPS1a<sup>2,4</sup> (left) and invariant mass spectrum of the heavy neutralino/chargino decay chains<sup>5</sup> (right). The dilepton OS-SF lepton edge of  $\tilde{\chi}_4^0$  is the edge between  $200 \text{ GeV} < m_{ll} < 400 \text{ GeV}$ .

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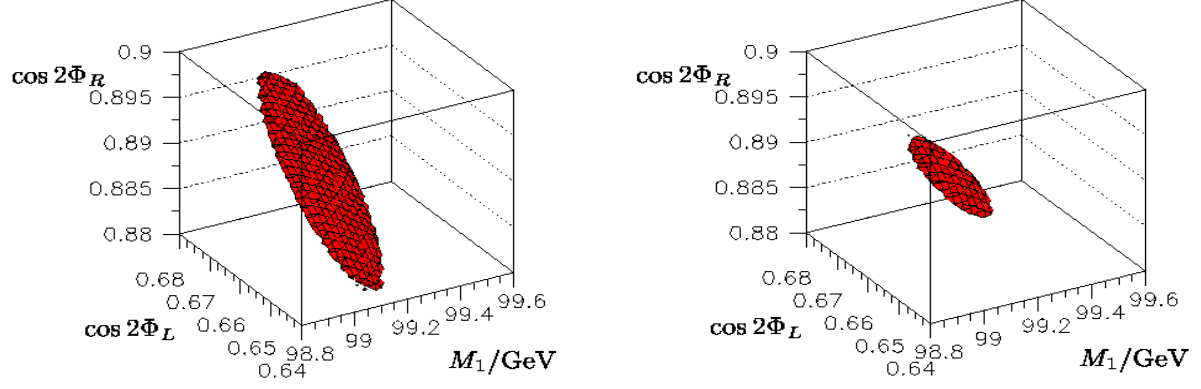


Figure 2: The  $\Delta\chi^2 = 1$  contour in the  $\{M_1, \cos 2\Phi_L, \cos 2\Phi_R\}$  parameter space derived a) from the LC data and b) from the joint analysis of the LC data and LHC data<sup>1</sup>.

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